CONSIDERATIONS IN SELECTION OF DC MOTORS FOR LIGHTWEIGHT ARMS

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ABSTRACT

This paper addresses the relationship between the weight of DC moving-coil permanent-magnet motors and the requirements for the driven motion. The requirements for motion are assumed to be made in terms of a maximum absolute velocity and a maximum absolute acceleration. A move consists of periods of maximum acceleration and periods of maximum velocity, so called trapezoidal velocity profiles. The load on the motor/drive-train is characterized by a maximum torque (or force) which is assumed to occur during a period of maximum acceleration.

The DC motor is assumed to be limited by a maximum torque applied magnetically to the armature (essentially a maximum current) and by a maximum armature speed. Within these constraints simple procedures for identifying the lightest motors are given. An analysis of several series of popular motors is provided which defines the current state-of-the-art for such motors.

NOMENCLATURE

ArmTorq	Torque applied to the arm
ArmVel	Arm velocity
AccTime	Time to reach maximum velocity
Beta	Average torque/maximum torque for arm
Eta	Motor duty cycle
F1	Maximum steady power of motor
F2	Maximum rate of power increase for motor
F3	Two times the maximum kenetic E. of motor
G1,G2,G3	Constant used to relate motor mass to F1,F2,F3
G1P	G1/Eta^0.5
G2P	G2/Eta
Imax	Maximum current
JLoad	Load inertia
JArm	Arm inertia
MaxArmTorq	Maximum ArmTorq
MaxArmAcc	Maximum arm acceleration
MaxArmVel	Maximum ArmVel
MaxPwrRate	Maximum rate of increase of motor power
MaxArmPwrRate	Maximum rate of increase of needed arm power
MovAngle	Angle of arm motion
MtrMass	Motor mass
MtrTorq	Torque of motor
MaxMtrVel	Maximum motor speed (rad/sec)
MovTime,T	Time for one complete move
MinMtrMass	Minimum motor mass
N,N1,N2	Gear (or coupling) ratios
TC	Cycle time for moves
TorqL	Constant load torque as from gravity
^	Exponent
*	Multiplication

SELECTION OF MOVING COIL MOTORS

In this section we consider some details in the selection of permanent-magnet DC moving-coil motors and the coupling ratio between the motor shaft and the manipulator link. It is assumed the objective is the lightest motor which is compatible with the load. Choice of the coupling ratio (or gear ratio) has an important role in minimizing motor weight and also affects motor armature power dissipation and total power input to the motor. Certain characteristics of DC moving coil motors prevent the selection of a zero weight motor. In this report one or more of the following will be assumed to be the limiting factor.

1. Maximum allowable energy dissipation in the armature over the load cycle.
2. Maximum allowable output torque (at zero acceleration) generally limited by maximum allowable instantaneous current.
3. Maximum allowable shaft speed.

That is, temperature, torque and speed will be considered to be the basic limits of an electric servomotor's performance. As is frequently the case in optimization problems all three of these limits enter in many situations. If the load characteristics are known, one can select a coupling ratio that will result in the lightest motor (or some other desireable characteristics).

Discussion of Coupling (or Gear) Ratio

If a single coupling ratio must be chosen, and such is assumed to be the case here, it can be chosen with one or more of the following objectives in mind.

1. Minimize power dissipation in the motor armature
2. Minimize power input to the motor
3. Maximize output torque to the load
4. Match desired load speed to maximum motor speed
5. Minimize coupling system weight and volume
6. Maximize coupling system stiffness

In this paper the last two objectives are ignored on the basis that the weight, volume and stiffness of the coupling system (as well as other mechanical parameters, e.g. reliability and cost) are more strongly influenced by the technology chosen for the drive train that the coupling ratio itself. An exception may be for a coupling ratio of one. The first four objectives are closely linked to the objective of minimizing motor weight for a given manipulator load specification.

Discussion of Manipulator Motion Characteristics

In most material handling tasks the velocity which a robot end effector moves is not constrained by the task itself; rather, various points on the path are fixed in location and/or velocity. The choice of velocity profile will have an effect on motor weight and coupling ratio. Typically there will be other limitations such as

1. Maximum acceleration of the link for structural integrity of the arm and payload.
2. Maximum velocity of the link (or end point) for safely.

Within these constraints it is often desireable to minimize total time of motion.

SPECIFIC PROBLEM STATEMENT

In light of the various considerations discussed above an approach to simplifing the problem is proposed here and used in what follows. The objective is an appreciation of what weight of motor is likely to be required for various classes of applications rather than a precise methodology for selection of a motor for a specific application.

Assume:

1. A single rotary link.
2. The torque supplied by the motor and drive train to the driven end of the link is ArmTorq and a known function of time. The maximum arm torque, MaxArmTorq, occurs during a period of MaxArmAcc.
3. Velocity profiles ArmVel(t) are limited by the maximum acceleration, MaxArmAcc, and speed, MaxArmVel, determined by external factors and the motor and gear ratio are to be chosen to be able to meet these requirements for performance.
4. The DC motor is limited by a maximum instantanious torque applied to the armature windings by the magnetic field and a maximum instantaneous speed, MaxMtrVel; however, these limits may be set below the absolute maximums of the motor by considerations of heating and reliability. The motor friction and windage losses are neglected so that the armature can be modelled as a pure inertia.

To summarize, the problem at hand is (1) to drive a load (2) with a velocity profile characterized by a maximum acceleration and velocity (3) with a friction free DC servomotor itself limited by a maximum applied torque and speed of the armature (4) through a drive train with a single coupling ratio where (5) the maximum applied torque occurs during a period of maximum acceleration. One of the results of the assumptions made here is that the velocity profiles considered are what are called trapezoidal or in the case of short motions triangular.

RESULTS

Given that the specifications call for a link acceleration capability of +-MaxArmAcc subject to a maximum speed of |ArmVel| <= MaxArmVel. Then the gear ratio which yields the lightest motor is the lesser of

$$N1 = MaxMtrVel/MaxArmVel \tag{1a}$$

or

$$N2 = 2*MaxArmTorq/MaxMtrTorq \tag{1b}$$

and the motor must meet the requirements that

$$MaxArmPwr <= F1-F3/AccTime \tag{2a}$$

if N1 is the gear ratio (where AccTime = MaxArmVel/MaxArmAcc) or

$$MaxArmPwrRate <= F2 \tag{2b}$$

if N2 is the gear ratio, where F1, F2, and F3 are defined as motor characteristic parameters

$$F1 = MaxMtrTorq*MaxMtrVel \text{ (=max steady power)} \tag{3a}$$

$$F2 = MaxMtrTorq\text{^}2/(4*JMtr) \text{ (= max rate of power increase)} \tag{3b}$$

$$F3 = JMtr*MaxMtrVel\text{^}2 \text{ (=2*max K.E.)} \tag{3c}$$

An interpretation of Eq. (1)-(3) is as follows. Eq. (1) states that the gear ratio must be picked so as to provide the required acceleration (1b) while not exceeding the maximum speed capability of the motor (1a). Eq. (1b) gives the gear ratio which will provide the maximum torque to the arm after the "gear box." The factor of two comes from the fact that for an optimal gear ratio one-half of the available torque at the armature will be used to overcome the inertia of the motor armature itself. However, this gear ratio may result in overspeed of the motor--thus Eq. (1a)

Eq. (2) states that the motor must have sufficient power (2a), and sufficient rate of power increase to meet the load requirements (2b). If N1 is the gear ratio the maximum power is achieved at full motor speed. If N2 is the gear ratio then the motor never reaches full speed and the most demanding condition is associated with the ability of the motor to accelerate. The maximum arm power and maximum arm power rate are functions of the arm characteristics and performance specifications. They are not related to the choice of motor or coupling ratio.

$$MaxArmPwr = MaxArmTorq*MaxArmVel \tag{4a}$$

$$MaxArmPwrRate = MaxArmTorq*MaxArmAcc \tag{4b}$$

In these equations MaxArmTorq need not occur at MaxArmVel but must occur during a period of MaxArmAcc.

Eq. (3) provides the definition of the essential motor characteristics. These are functions of the motor choice only and are not related in any way to the arm characteristics and arm performance specifications. Although Eq. (3) depends on 3 motor characteristics, MaxMtrTorq, MaxMtrVel and JMtr, it is easy to verify that the three factors F1, F2 and F3 are related by

$$F1^2 = 4*F2*F3 \qquad (5)$$

and hence one needs only two of the three factors to describe the motor's performance.

To summarize, Eq. (2) provides the necessary and sufficient conditions for adequate motor capabilities for a specified arm design and performance. Eq. (3) gives the MOTOR characteristics while Eq. (4) summarizes the ARM design and performance characteristics. Eq. (1) is necessary only to find the gear ratio or coupling ratio given the assumptions of this simplified problem. The assumtions are (1) that the velocity profiles are considered to consist of intervals of maximum acceleration (or decleration) and intervals of maximum velocity, (2) that the maximum torque does occur during a period of maximum (or minimum) acceleration and (3) that the motor is constrained by both a maximum torque applied to and a maximum speed of the armature. Frictional losses in the gear train and in the motor can be reflected back as part of the MaxArmTorq. Inertial torques associated with the drive train should also be reflected back as part of MaxArmTorq. Some iteration may be required because the coupling ratio is unknown.

To find the lightest motor among a set of motors calculate F1, F2 and F3 for each motor in the set and select the lightest which meets the inequality constraints Eq. (2). Since F1, F2 and F3 are monotonically increasing functions of weight for a given level of technology the task of finding the lightest motor is simplified by plotting F1-F3/AccTime and F2 versus weight and interpreting the constraints graphically. An example problem has been worked in the Appendix.

A number of motors from various manufacturers have been examined and the current technology for DC moving coil servomotors is given VERY APPROXIMATELY as follows.

$$F1 = G1*MtrMass/Eta*0.5 \qquad (6a)$$

$$F2 = G2*MtrMass/Eta \qquad (6b)$$

$$F3 = G3*MtrMass \qquad (6c)$$

where G1, G2 and G3 are constants denoting the level of technology. The APPROXIMATE values for a typical technology are

$$G1 = 50 \text{ (ft.lb./sec.)/lb.} \qquad (7a)$$
$$G2 = 100 \text{ (ft.lb./sec.^2)/lb.} \qquad (7b)$$
$$G3 = 6.25 \text{ ft.lb./lb.} \qquad (7c)$$

Eta is the duty cycle expressed as a fraction of time that the current (or torque) is at the maximum allowed (with the remainder of the time at zero current). These relationships can not be used for small Eta (less that 0.01) where thermal loads are no longer the limiting factor. The data used to derive the relationships was for motors in the range of 4 lb. to 80 lb. Figures 1 and 2 give actual values of F1 and F2 for six different series of popular DC moving coil motors. The data is for a duty cycle of Eta = 0.25 and is based on the manufacturer's specifications. Because of the source of the data the actual manufacturer is not given. The data in these figures serves more to define the state of the art than to provide a firm basis for choosing a motor.

An equivalent duty cycle, based on thermal heating, can be calculated by considering the cycle given in Figure 3. This is a cycle that results from a load that is a combination of a pure inertia plus a steady torque. As before the velocity profile is trapezoidal. Beta is the ratio of the average torque to the maximum torque. In this case

$$Eta = 2*(1-Beta)^2*AccTime/TC+Beta^2 \qquad (8)$$

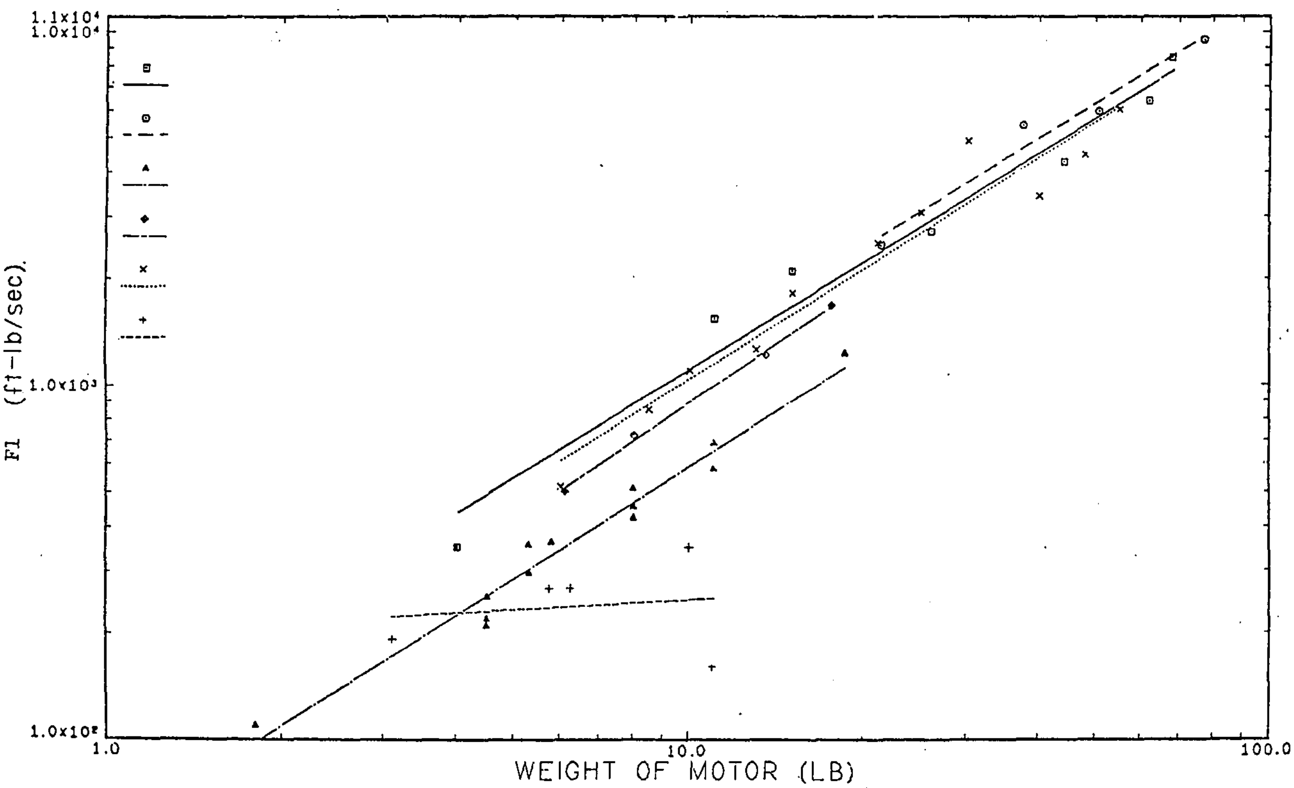

Figure 1 Power Versus Weight for DC Motors

Selection of MaxArmVel and MaxArmAcc has a strong influence on the motor size and motion times of the manipulator.

MotionTime = MoveAngle/MaxArmVel +AccTime (9a)

or

MotionTime^2 = 4*MovAngle/MaxArmAcc

whichever is greater. Using Eq. (9a) and (2a), the usual case, and Eq. (6) there results

MtrMass = (JArm*MaxArmVel^3)/ (10)

[G1P*(MovTime*MaxArmVel-MovAngle)-MaxArmVel*G3]

for the case of a PURELY INERTIAL LOAD. Naturally attempts to reduce travel time result in increased motor weight; however, for any specified travel time and travel distance and the various load parameters there is an optimal choice of MaxArmVel and MaxArmAcc that minimized motor weight as follows.

MinMtrMass = 27*JLoad*MovAngle^2/(4*G1P*MovTime^3) (11)

for

MaxArmVel = 3*MovAngle/[2*MovTime-G3/G1P)]

and

MaxArmAcc = 9*MovAngle/[2*(MovTime-G3/G1P)*

(MovTime-2*G3/G1P)]

The various relationship presented here are derived in [1].

CAVEATS AND CONCLUSIONS

The preceding analysis is greatly simplified to bring out the most significant relationships. An application will need to be carefully analyzed to make certain that motors are not overdriven. Use of temperature sensors or realtime computerized analysis of motor thermal loads could be part of an actual control system to enable maximum performance of a robotic system in the face of varying load requirements. As a general rule loads can only be specified statistically. In many situations a rather small load factor, Eta, would be the result meaning a rather light motor could be used. When the robot encountered a particularly demanding task the controller would be "smart" enough to automatically derate the robot. That is reduce MaxArmVel and MaxArmAcc.

An excellent way to reduce motor weight is by reducing the parasitic load associated with the arm itself. This means lightening other components of the arm and placement of components in locations where inertial loads are minimized.

Motors can be cooled by forced air or other active means to increase their effective capacity.

Motions other than trapezoidal or triangular velocity profiles are desireable for purposes of:

1. Reducing maximum voltage to the motor. DC moving coil motors are characterized by a large back EMF.

2. Reducing energy dissipation in the windings. This is equivalent to reducing the load factor. An optimal strategy is often nearly a linear variation in current during a motion. This gives a parabolic velocity profile rather than trapezoidal and as a rule of thumb will reduce energy dissipation by about 10% for the same move time[2].

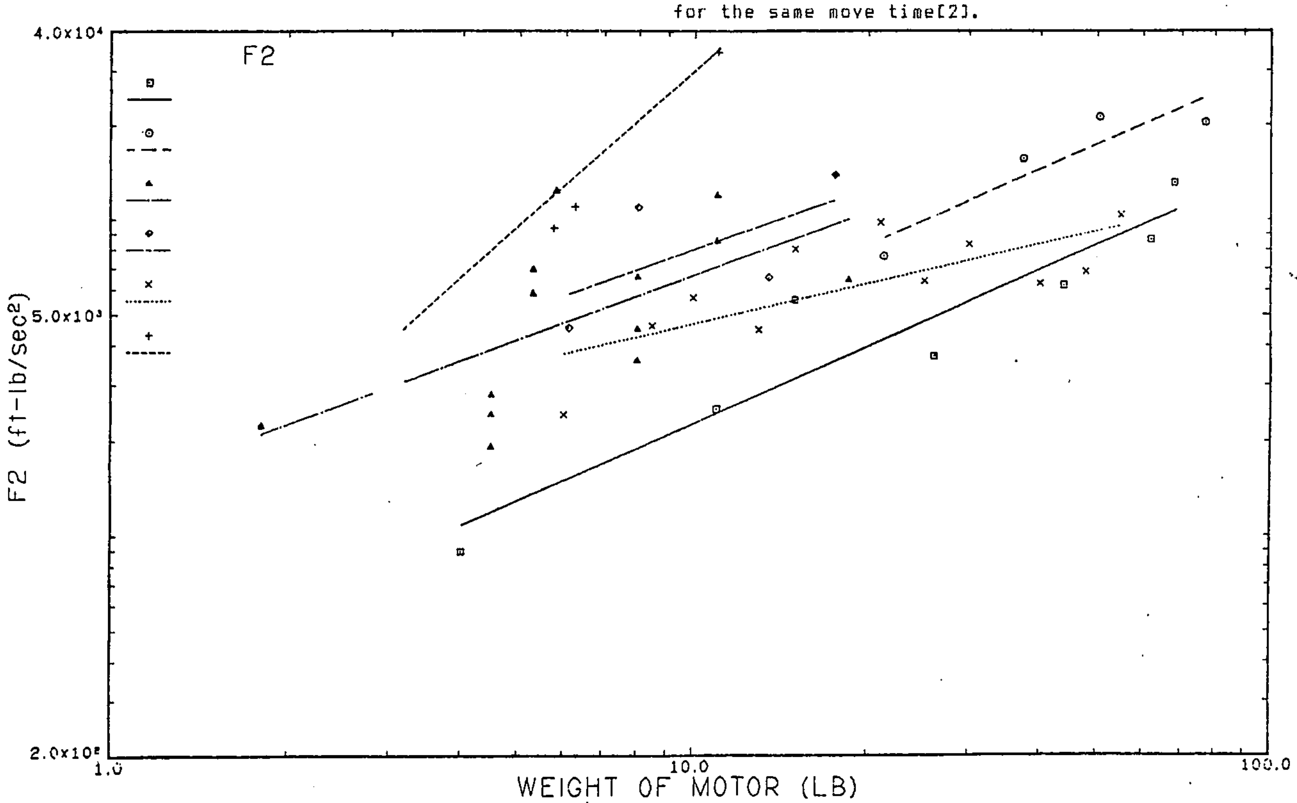

Figure 2 Rate of Power Increase Versus Weight

3. Reducing excitation of structural dynamic modes or "vibrations". Because of the structural deflections a trapezoidal velocity profile at the driven end will not result in a trapezoidal velocity at the load end and will leave the load end vibrating. The resolution of the control problem for flexible structures is a very important problem for lightweight motion systems.

4. Better control of terminal accuracy. Even if the elements of the motion system were rigid it would be impossible to arrive at the desired end position precisely with a trapezoidal velocity profile.

For all of the above reasons a motion will not actually be made using the trapezoidal profiles assumed here. However, the motion profiles for significant changes in position may often be approximated by trapezoidal or trianglar profiles. Small motions on the other hand will generally use much different velocity profiles but for these moves the power capabilities of the motor is not a factor.

This paper has dealt only with permanent magnet moving-coil motors. These motors are usually considered "best" for high performance electric servos because of their high acceleration capabilities and their relatively low weight and high efficiency. A very promising alternative is permanent magnet brushless DC (or AC) motors.

ACKNOWLEDGEMENTS

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REFERENCES

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2. Electro-Craft Corporation, DC Motors, Speed Controls and Servo Systems, Fifth Edition, 1980.

3. Various data sheets of DC motor manufacturers.

APPENDIX

Assume a load equivalent to a 100 pound mass being moved horizontally at a radius of 6 feet. A motion of one radian is to be achieved in one second from stop to stop with a one second rest between motions. A MaxArmVel of 1.5 rad/sec with a MaxArmAcc of 4.5 rad/sec^2 will achieve the desired speed of motion. Assuming the load is entirely inertial the result is:

JArm = 100*6^2/32.2 = 111.8 ft.lb.sec.^2
AccTime = 1.5/4.5 = 0.333 sec.
Eta = 0.667/2 = 0.333

From which:

MaxArmTorq = 111.8*4.5 = 503 ft.lb.
MaxArmPwr = 503*1.5 = 755 ft.lb./sec.
MaxArmPwrRate = 503.1*4.5^2 = 2264 ft.lb./sec.^2

The motor must meet the requirements of Eq. (2). This means that 2264 <= F2 and 755 <= F1-F3/AccTime. The minimum motor weight could then be estimated by (1) using actual data from motors for F1, F2 and F3 or (2) using the very approximate estimating relationships of Eq. (6) and (7) or (3) using the power law regression lines in Figures 1 and 2.

Using the approximate relationships of Eq. (6) and (7), for Eta = 0.333

2264 <= 300*MtrMass

or

MtrMass >= 7.55 lb.

and

755 <= 67.9*MtrMass

or

MtrMass >= 11.1 lb.

Since the MtrMass is constrained by maximum power the implication is that the gear ratio will be set by N1 or Eq. (1a). That is N = N1 =MaxMtrVel/MaxArmVel. Reference to actual manufacturer's specifications in Figures 1 and 2 show that there are motors as light as 10 lb. that would be satisfactory.

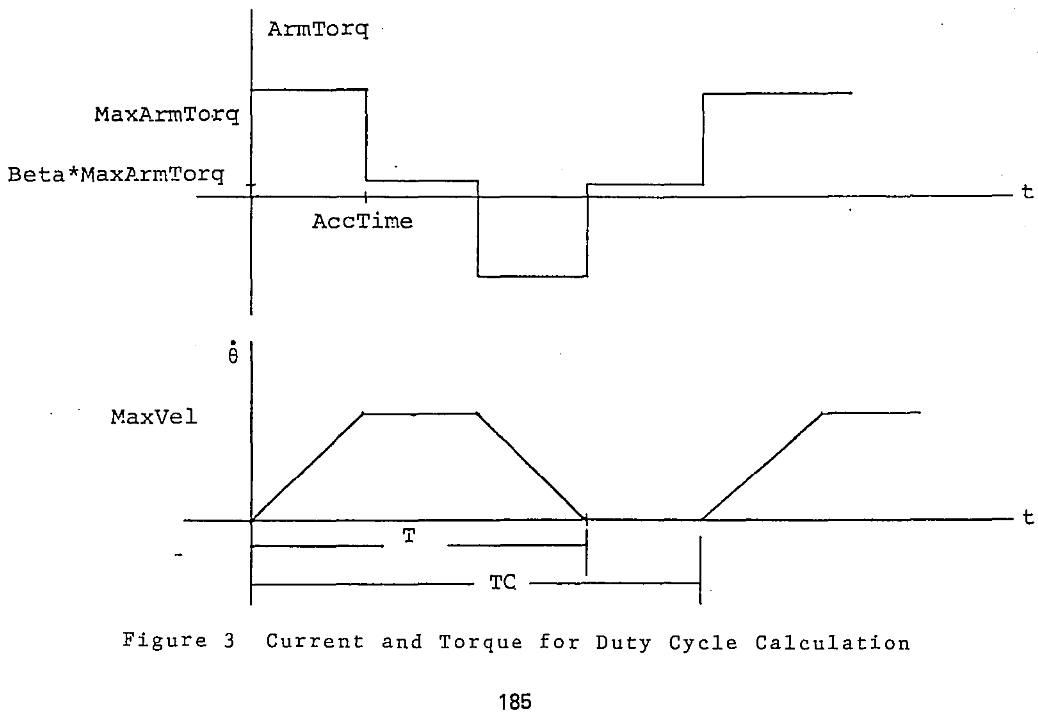

Figure 3 Current and Torque for Duty Cycle Calculation